MACLEAN-ESNA

Maintaining Fastener Tightness Manual

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WHAT THE DESIGNER WANTS OF A THREADED FASTENER SYSTEM

Threaded fasteners have proved to be the most efficient and effective way to put together shapes that would be impractical as one piece structures. They also simplify, or reduce costs, or make practical the disassembly of such structures for safety inspection, cleaning, repair or rebuilding.

When a vehicle, structure or machine is overhauled, its worn and corroded parts may be replaced as a routine maintenance operation. However, the threaded fasteners are not generally regarded as things that wear out or deteriorate. They are expected to be reusable.

Fasteners must carry loads, of course. They resist various combinations of tension and shear loading, usually without permitting any significant relative movement of the fastened parts. Most threaded fasteners are screwed up tight so that they clamp the fastened parts together. It is desirable to maintain this initial clamping force — or as large a portion of it as possible.

Although their primary function is to permit convenient assembly and disassembly, threaded fasteners are expected to stay in place between those events. Without fail!

Characteristics the designer wants, then, are reliability, strength, tightness and convenience in service. He looks for ways to combine all these ideals economically.

WHY

DO THREADED FASTENERS LOOSEN?

The fastener that loosens and falls off has failed as completely as if it had ruptured. A bolt or stud that is strong enough to carry its service load when tight, may fail from fatigue if the joint loosens enough to "rattle" — or even if some of the initial clamping force is lost. In fact, in the case of a pre-stressed joint failure has occurred as soon as the pre-stress is lost — which may be a long time before the bolt "rattles".

Load-carrying reliability of a fastener, thus, depends not only on its strength but also on its ability to stay in place — to stay tight. Anything that affects loosening is just as important as the metallurgy of rupture under stress or any other design requirements. Performance depends on both factors.

We know that threaded fasteners on static structures (one not subject to shock vibration or impact) do not loosen and fall off. From this basic starting point, investigators have gone on to pin down what does happen. In 1945, Goodier and Sweeney(1) reported that cyclic tensile loading of plain nuts and bolts causes extremely small amounts of nut rotation. In 1950, Dr. J. Sauer and D. Lemmon(2) reported that this rotation stops after the first 2,000 load cycles and does not exceed about 2 degrees. Tests with oscillatory wrenching torques reported in 1966 by Clark and Cook(3) indicated that it takes relatively large torques to cause loosening, while a tight fastener system can withstand small torque oscillations indefinitely without loosening.

It is well known that nuts and bolts tend to loosen if the machines they fasten are subjected to vibration or repeated impacts. A generally-accepted theory explains how motion of the fastened parts can cause turning of a nut on a bolt. To visualize this situation, consider a weight resting on an inclined plane. If static friction exceeds the component of weight that tends to cause sliding, the body remains at rest. If the plane surface is vibrated or if mechanical shocks are applied to it, the effective coefficient of friction is reduced. As vibratory motion of the plane surface becomes more intense, a point can be reached where the weight begins to slide down the plane.

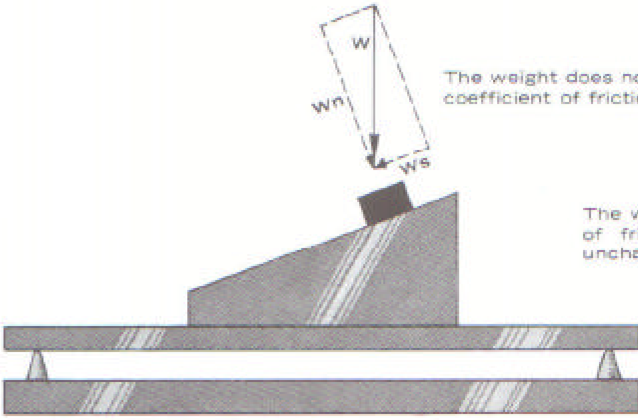
For a closer analogy, visualize a spring compressed by a wedge in a clamping system. Again, a point is reached as vibratory action reduces friction forces to a critical level where relative motion is induced. When the system "chatters" the wedge begins to "walk." Spring energy will tend to back it out.

A loose nut on an axially vibrating bolt will tend to "walk" up and down the bolt. The mechanism is much the same as the case of the sliding weight or the wedge.

1. "Loosening by Vibration of Threaded Fasteners"
J.N. Goodier & R.J. Sweeney **Mechanical Engineering**
December 1945

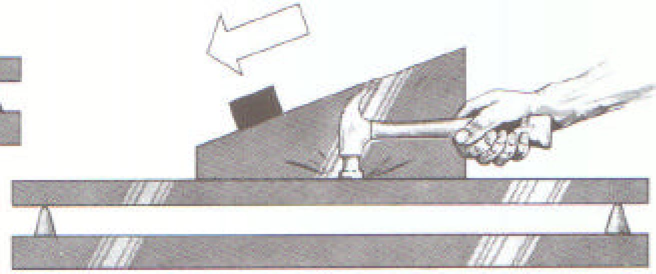
2. "Bolts — How to Prevent Their Loosening"
J.A. Sauer, D.C. Lemmon, E.K. Lynn **Machine Design**
August 1950

3. "Vibratory Loosening of Bolts"
S.K. Clark & J.J. Cook. SAE Paper #660432



The weight does not slide as long as **Wn** times the static coefficient of friction exceeds **Ws**

The weight slides when vibration reduces the effective coefficient of friction, although weight components **Wn** and **Ws** remain unchanged.

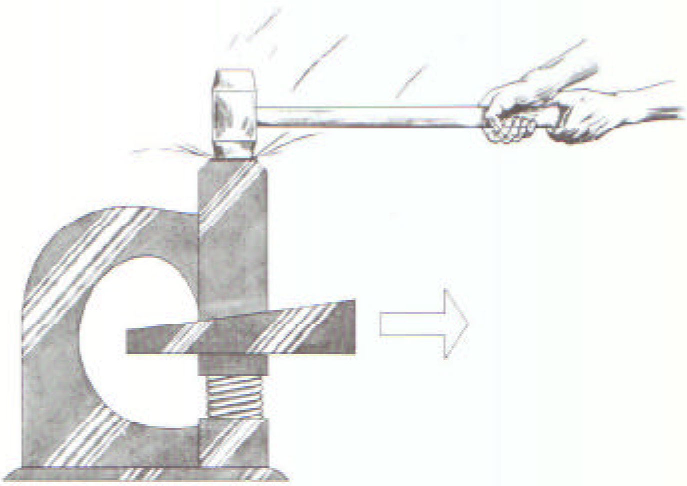


Vibration reduces the effective coefficient of friction and provides energy. Masses and shapes are never perfectly symmetrical, and consequently that energy produces motion. But this is only a partial explanation of how and why fasteners loosen.

While laboratory and theoretical investigations were being pursued in many other places, research at ESNA® was centered around vibration testing. Thousands of threaded joints were being shaken until they came apart. Some withstood vibration better than others. This showed the way toward design improvements. Testing also proved to be a reliable tool comparing various locking devices and this, in turn, was useful in efforts to predict service performance.

Yet the mechanism of fastener loosening under vibration was still not explained satisfactorily. It is true that the nut turns on the bolt during a vibration test. This, however, does not occur until rather late in the test. It is a near-terminal phenomenon. A great amount of evidence suggested that something important happens before the nut turns.

The breakthrough in understanding came when the preliminary phenomenon was identified. Theoretical and experimental work showed that the critical change is a loss of pre-stress induced by vibration.



Each time an impact excites a pulse of elastic waves in the clamping system, the wedge "walks" out a short distance. Vibration acts almost as a lubricant.

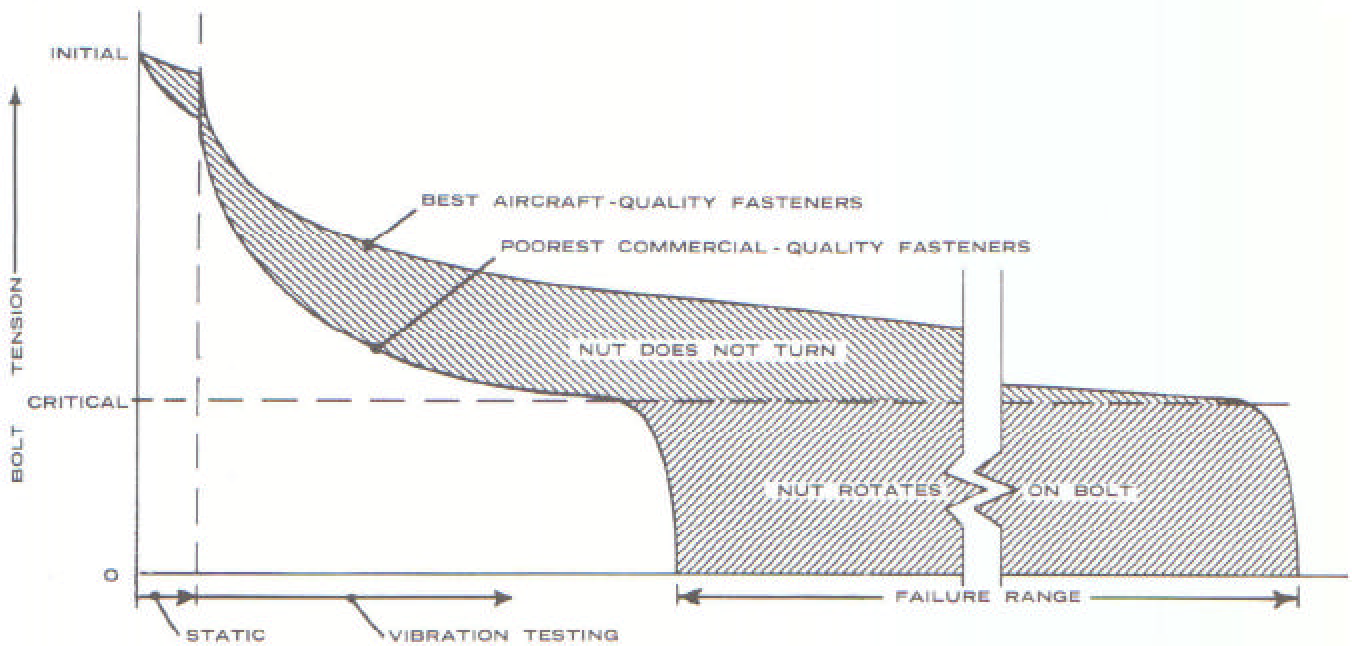
In this schematic illustration of a threaded fastener, **A** represents vibratory impulses, and **Ar** represents the component that would tend to cause rotation if those impulses should become unbalanced in one direction or the other.

FASTENERS FIRST LOOSEN WITHOUT TURNING!

"Settling down" is the term ESNA® laboratory people use to describe a relaxation phenomenon that occurs at room temperature under static conditions. During the first few hours after a nut and bolt are tightened on an arbor, the fastener system has lost some of its pre-stress.

The mechanical fits and finishes involved determine to a great extent how much initial clamping load will be lost. With precise, well-finished parts, this relaxation may be limited to 2 or 3 per cent of pre-stress. With rough surfaces, loose thread tolerances and lack of squareness,

Schematic of all-metal fastener testing histories shows how bolt tension is lost first in the static condition and then, more rapidly, after vibration begins. The nut turns at a critical tension level.



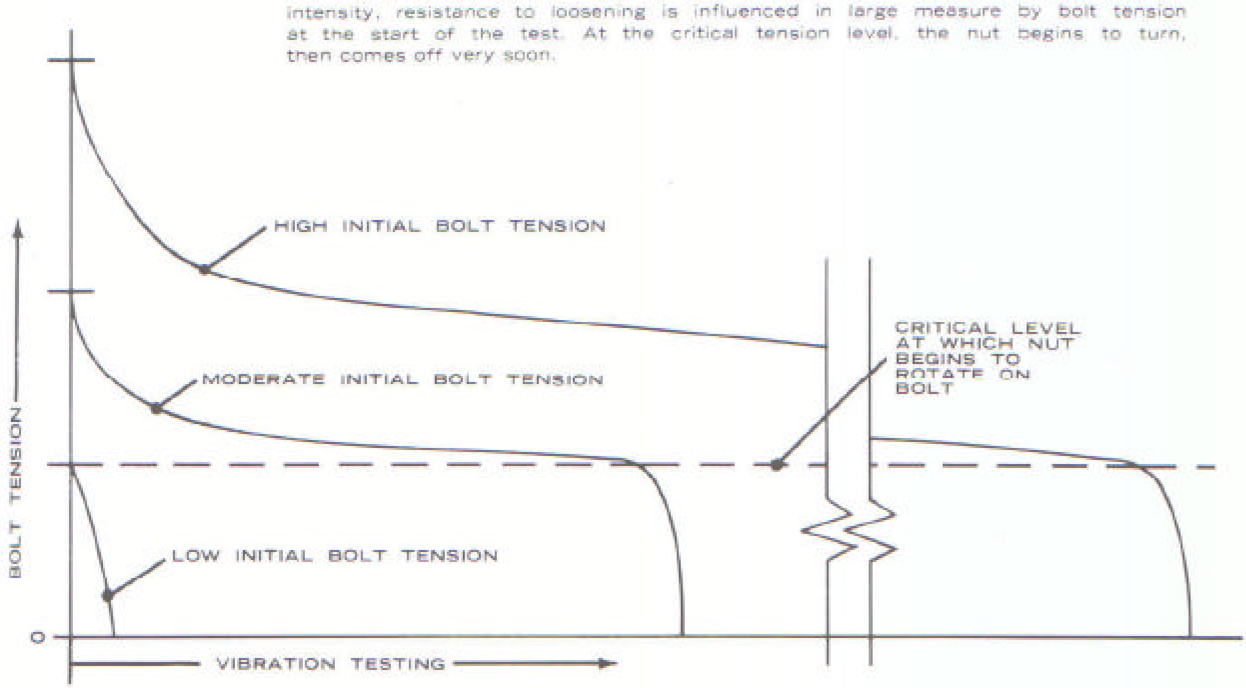
as much as 10 per cent of the original loading may be lost.

This stress relaxation is analogous to high-temperature creep. We suppose that it involves a gradual adjustment as localized zones stressed beyond the yield point transfer load to adjacent metal. Another mode of relaxation was observed by Professor Wright[4] of the University of Illinois in connection with torque-tension studies of bolting for structural steel. He found that part of the pre-stress loss that occurred within a few hours after tightening was accounted for by rotation of one end of the bolt as it recovered from being twisted during tightening.

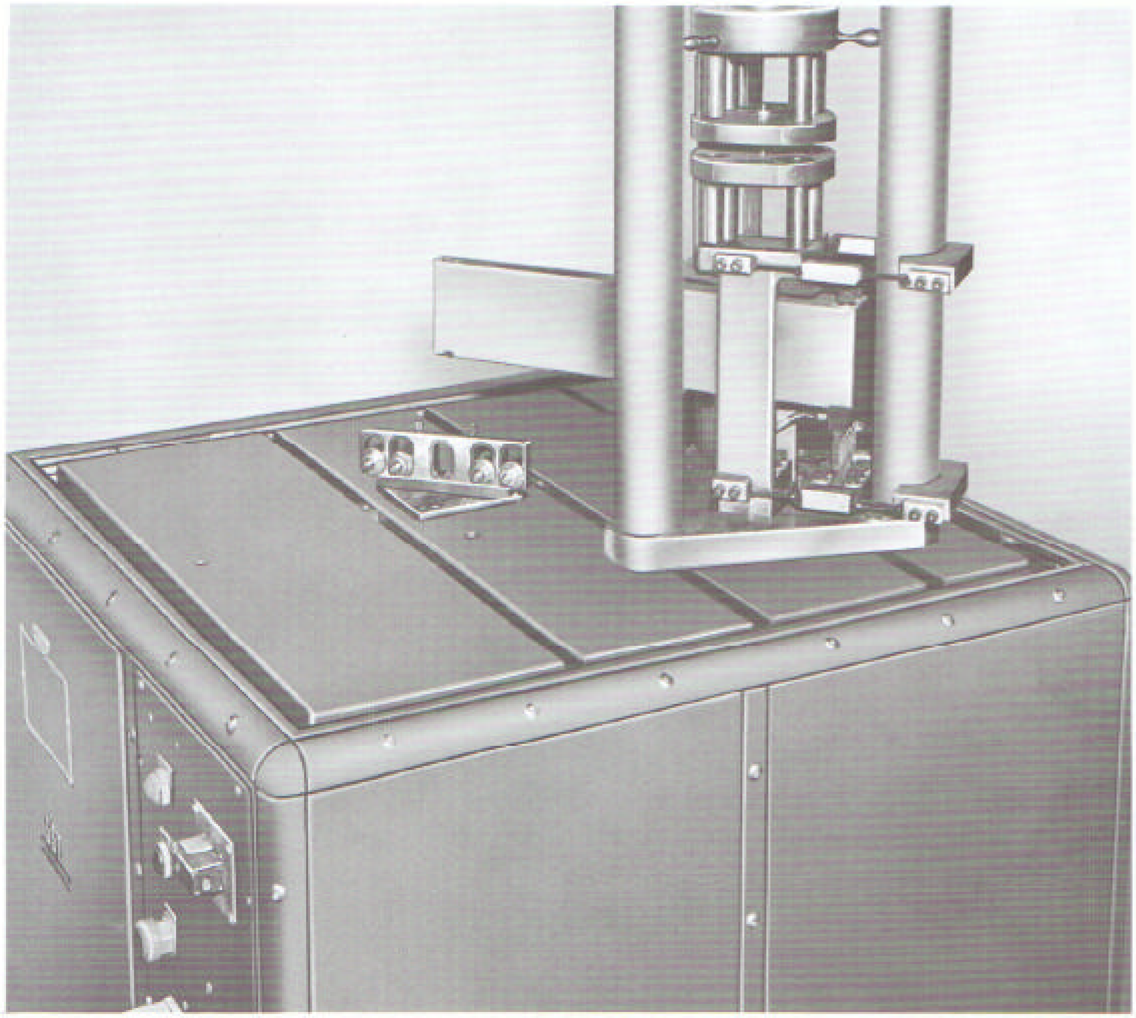
When a retightened fastener system is subjected to a vibration test, loss of clamping force continues, but at a rate much slower than occurred initially. The nut does not turn on the bolt while that is happening. Nevertheless, bolt tension decreases as the vibration test progresses.

The mechanism of loosening in this phase — before any relative thread turning occurs — is not known accurately. It is probably a combination of local yielding and wear. The vibrations tend to hammer down and wear away minute metal projections on all bearing surfaces.

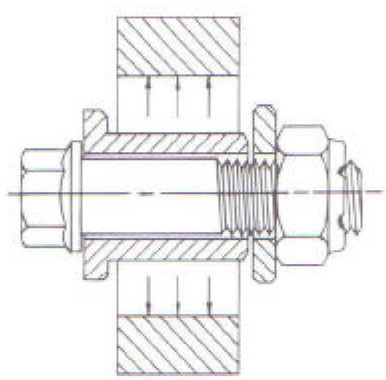
For any given nut type — plain or self-locking — and a given level of vibration intensity, resistance to loosening is influenced in large measure by bolt tension at the start of the test. At the critical tension level, the nut begins to turn, then comes off very soon.



4. "Laboratory Tests of High Tensile Bolted Structural Joints"
W.H. Munse, D.T. Wright, N.M. Newmark
Paper Presented to Structural Division, American Society Civil Engineers, in Chicago on Sept. 8, 1952



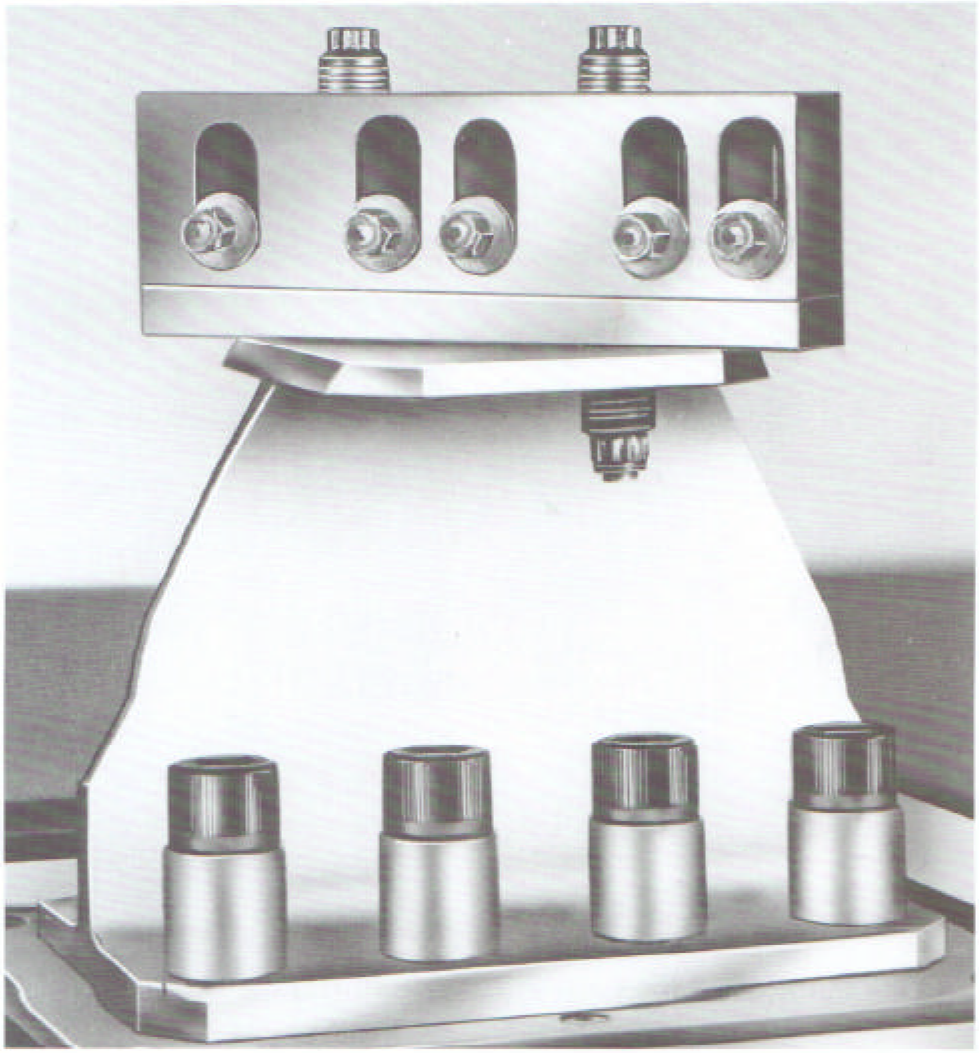
Fasteners are tightened on spool-like arbors, and their high-frequency vibration is excited by blows against the arbors.



VIBRATION TEST

In the past, self-locking nuts have been tested in vibration while loose on bolts or threaded studs. That does not yield information on the practical tight-bolt situation. The test which ESNA®'s Research Department now finds most revealing is a relatively new vibration test for tightened fasteners.

It is controllable and to save time and expedite results, ESNA®'s testing is done on an accelerated basis. However, we have long since established that long-term, less severe vibration produces the same re-



As arbors reciprocate in the slotted fixture, they receive two impacts during each cycle of vibratory motion.

HAMMERS THE FASTENED PIECES

sults; it just takes longer to happen. ESNA®'s procedure, then, gives reasonably prompt information about how well a fastener system might be expected to perform in service. And it also provides a sound basis of comparison for measuring the performance of alternate fastening devices or methods.

A vibrating fixture has clearance holes or slots into which spool-like arbors are inserted. These arbors are held together by test bolts, and the test nuts are tightened to set up a service-simulating preload. As the fixture vibrates, it subjects each spool to an impact twice a cycle.

Number of impacts and severity of impacts are the variables that speed a loosening failure. Frequency of impact has no effect except that a certain number of blows can be struck in less time if the frequency is raised. Direction of impact — perpendicular or parallel to the bolt axis — has no significant effect by itself.

MECHANICAL IMPACTS SET UP RESONANCE

To trace the mechanical train of events between an impact against parts bolted together and a consequent loss of bolt tension, it helps to consider all the modes and all the resonant frequencies at which an ordinary mechanical assembly can vibrate.

All elastic systems, when they are excited mechanically, resonate in harmonic motion. This fact may call to mind such images as a vibrating string, a tuning fork or a spring-suspended weight. In all such systems, an increase of rigidity with respect to mass increases the resonant frequency. Complex systems may resonate in many modes, and each mode will have its own fundamental resonant frequency.

In the case of bolts and studs together with nuts and the parts they clamp together, such elastic sine-wave vibrations can and do occur. We know of no research in which the internal vibratory motion of fasteners has actually been measured experimentally. However, we have calculated their resonant frequencies for various modes of vibration. Lowest frequencies for typical fasteners are in the order of fifty thousand cycles per second, and they range up into millions of cps — or, in electronic terms, up in the mega-Hertz portion of the spectrum.

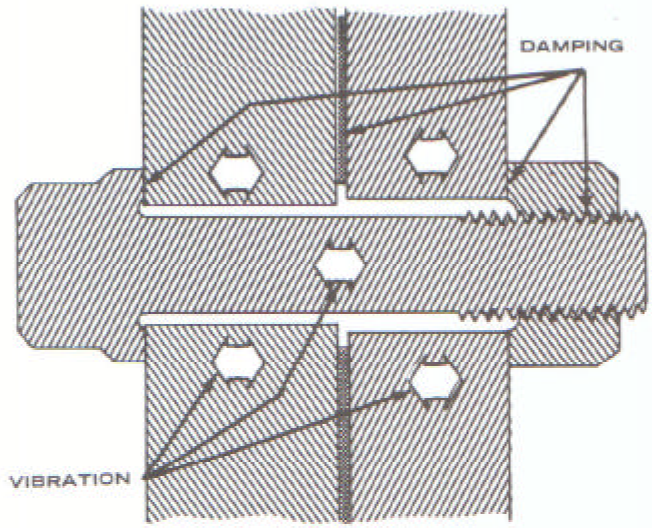
Vehicles, engines, tools and machines do shake, and sometimes they chatter or buzz. But mechanical vibrations even close to the mega-Hertz range are far beyond ordinary consideration. Any oscillations that occur at such ultra-high frequencies must be stimulated by exciting forces applied at much lower frequencies — or, perhaps, by sharp impacts. This, we believe, is the case for fastener loosening. Low frequency vibration or random impacts excite resonant frequencies in the fasteners.

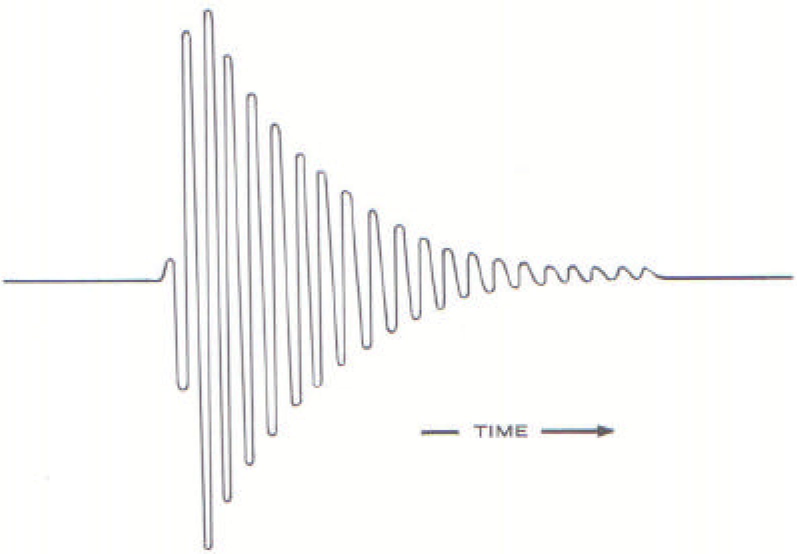
Repeated impacts occur in practical fastener environments because of explosions, valve actions, limit-stop impacts and similar occurrences. Intense low-frequency vibrations can set up steep shock waves at certain parts of a structure.

Because fastener resonant frequencies are so high in comparison with the repetition rate of the exciting waves, we cannot expect to find sustained resonance or vibration in the fastener system. More likely, each occurrence of vibration is damped out fairly rapidly by friction losses at interfaces and in the metal itself. Then, the fastener remains "at rest" for a comparatively long time until it gets excited to vibrate again. The number of impacts of a certain severity that occur during a vibration test, for example, is the significant variable — not the time-rate or frequency of impact repetition.

All the experimental evidence amassed by ESNA® indicates that when tightness of a threaded fastener is lost as a result of shaking or impact, a succession of damped, high-frequency resonant vibrations is the mechanical cause.

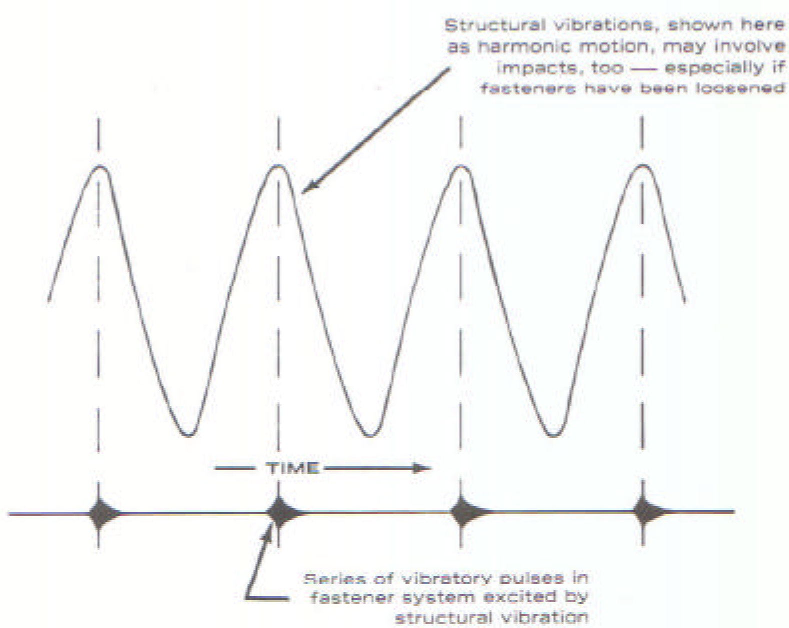
A simple mode of fastener vibration, indicated schematically here, is an axial tensile and comprehensive oscillation. Most of the damping probably occurs at the interfaces, but internal friction in the metal itself will also account for some energy absorption.





At the frequencies observable by conventional instrumentation, impacts set up pulses of mechanical oscillation with patterns like this. It is reasonable to assume that a similiar phenomenon occurs at the extremely high resonant frequencies of fastener systems.

The time relationship between structural vibration and the intermittent high-frequency wave pulses that such exciting motions set up in a fastener system is diagrammed here in highly schematic form.



ENERGY ABSORPTION IS THE KEY FACTOR

If fastener loosening is caused by repeated mechanical shocks which set up extremely high-frequency vibrations in fastener systems, there is not much hope of solving the problem by eliminating those shocks. They are characteristic of the fastener environment and cannot be avoided.

Sometimes a long bolt can be used instead of a short one. It may stay tight longer in a vibrating system because the same amount of vibration-induced wear will reduce its initial tension by a smaller percentage. But, as often as not, this cannot be justified in terms of cost, weight or space.

There is no practical way to "tune out" all the exciting forces either. Resonant vibrations of the fastener components are already far distant in the spectrum from frequencies of their exciting forces. The most effective course is to inhibit a fastener system's response to those exciting forces. This suggests energy absorption — damping out the fastener vibrations that do start.

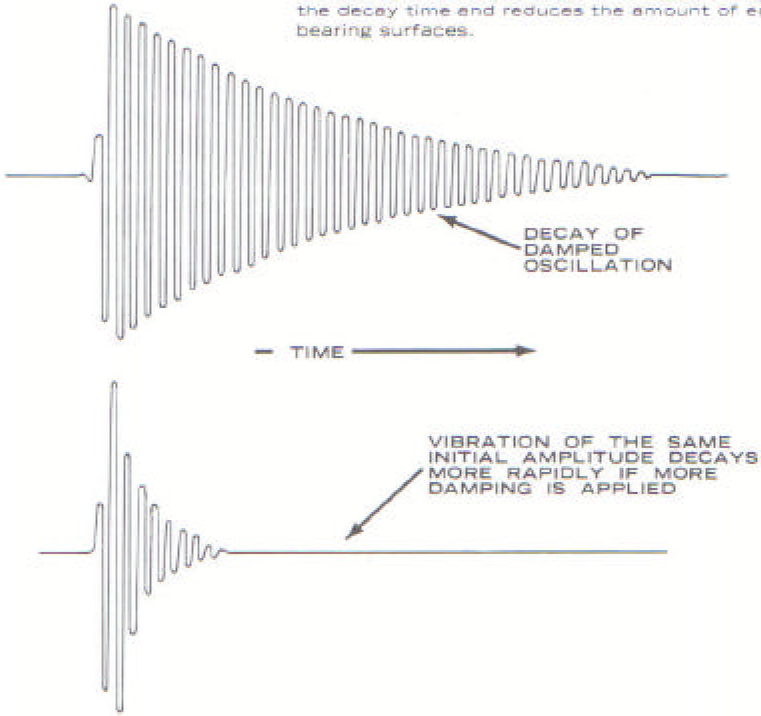
A measure of damping is already provided, of course. All mechanical structures dissipate energy as they vibrate. Otherwise they would never stop vibrating, once excited. A bell, once struck, would ring forever. It is possible to mute the bell drastically by soaking up its vibratory energy. Many different kinds of friction-producing or viscous restraints will accomplish this. Correspondingly in threaded systems, with their much higher resonant frequencies, the amount of "ringing" can be reduced sharply.

Damping, we find, is exceedingly beneficial. The loss of preload that occurs in a vibration test before the nut turns on the bolt is substantially reduced by damping. This phase of loosening is unaffected by the amount of locking torque present in the fastener.

Resistance to turning after loosening has started is enhanced considerably by damping, too. A relatively low locking torque or "prevailing torque" with damping is more effective than a high torque without it.

Viscous materials applied as thread lubricants tend to prevent loss of fastener prestress. Rubber applied in various ways in

Absorbing vibratory energy in a fastener system with added damping shortens the decay time and reduces the amount of energy available to wear away critical bearing surfaces.



the fastener system has the same effect. So do thread sealers and locking compounds as long as they do not get hard or turn into powder. These are all damping materials.

The initial decrease in pre-stress or clamping forces that occurs under static conditions is not, of course, affected by presence of a dynamic damper in the system.

On the other hand, the big drop in pre-stress that occurs, without rotation, under dynamic vibration and shock conditions can be decreased significantly by presence of almost any damping material in the threaded fastener system. This fact has been demonstrated beyond doubt by extensive testing.

Of all the pastes, "gunks", adhesives, rubbers and plastic materials available as energy-absorbers, there are no great performance differences to influence a choice as long as they all stay soft. However, there are other desirable characteristics that should be kept in mind.

The ideal energy absorbing system or material can be judged against a combination of requirements:

VIBRATION DAMPING

It should be effective in the extremely high frequency ranges at which fastener systems vibrate.

LONG LIFE

Shelf life and service life in a variety of environments should not cause deterioration.

REUSABILITY

A reasonable number of assembly and disassembly cycles should be endured without damage.

CONVENIENCE

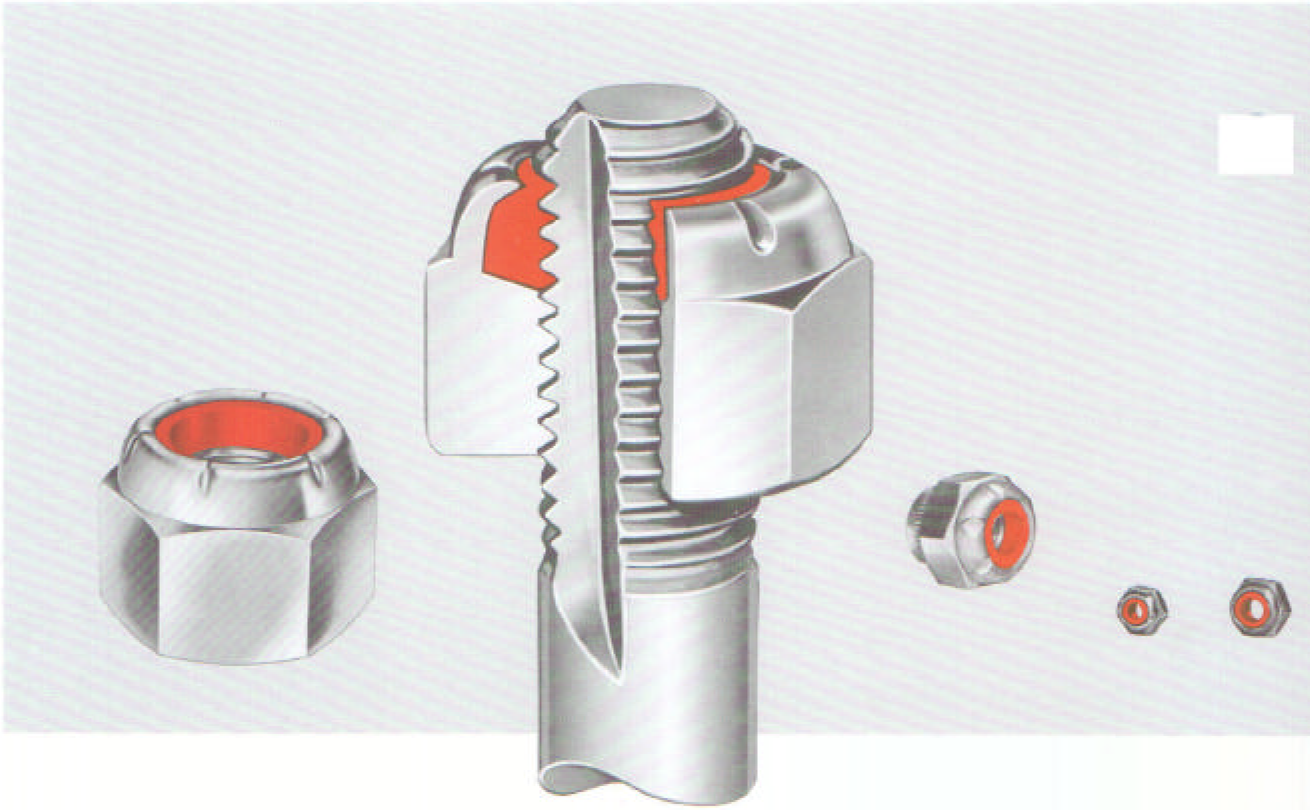
The system should not interfere with maintenance work — should not require extra operations.

THREAD SEALING

If the damping system seals along threads, that may be considered a bonus.

LOW COST

The foregoing merits are all cost savers, but low product cost is desirable, too.



NYLON

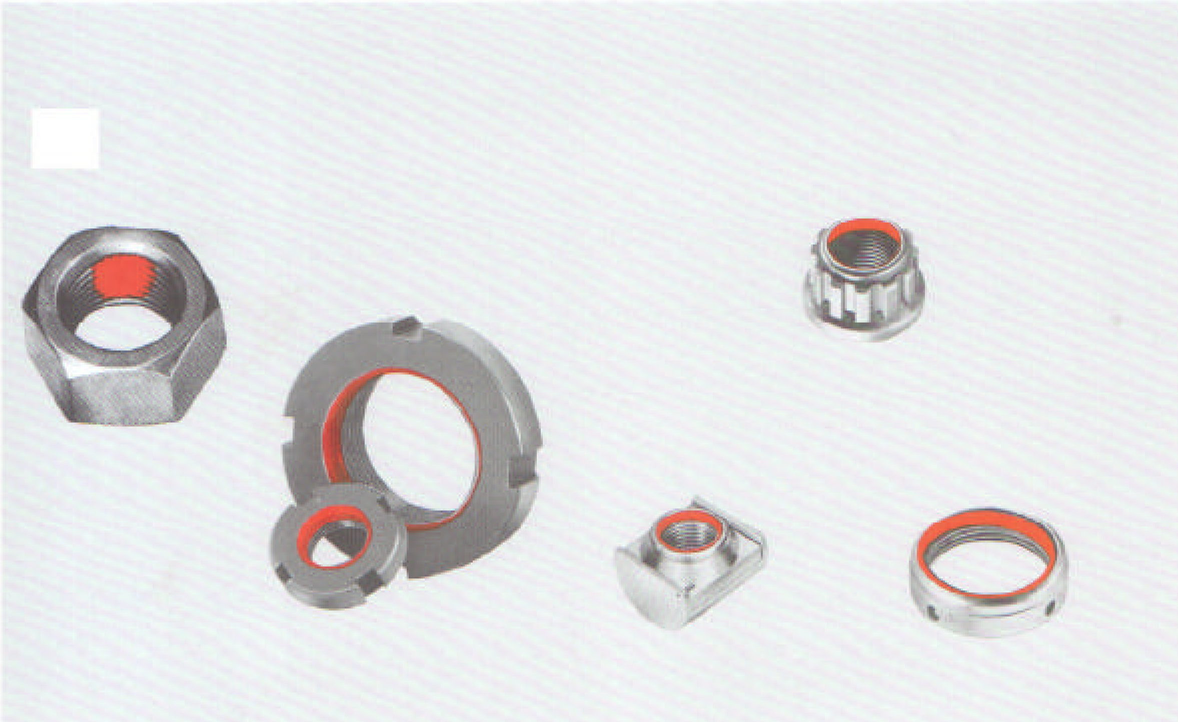
...MOST PRACTICAL AND EFFECTIVE ENERGY ABSORBER

Measured against all the practical requirements a fastener damping material must meet, nylon plastic emerges as a clear first choice. It is a good damper of high-frequency elastic waves in fasteners.

It stays in place. It lasts indefinitely in service. Nylon has a memory of its initial shape, and it tends to recover after deforming forces are released. It serves as a lubricant during assembly and disassembly.

The plastic does not harden, flake, powder or crumble. However, nylon is not a usable material at temperatures above about 350° F., and it is this one limitation that prevents almost universal use of nylon in self-locking fastener systems.

Where to place the energy-absorbing material in a practical nut-bolt system is a question with many answers. A nylon



Nylon is most effective as an energy-absorber when placed in the threaded area. The red nylon insert in the Elastic Stop® nut design (see cutaway) is deformed by the bolt threads when the nut is wrenched on the bolt and maintains continuous resilient pressure on the bolt threads. The ESlok® red nylon patch, bonded to the nut threads, and the Collarlok® fused 360° collar also deforms without being mutilated or cut. Nylon continues to serve as an effective damper even after a number of assembly and disassembly cycles.

washer in the bearing surface area under a nut or bolt head would absorb energy. It would be squeezed out of the system at high loads, though, and would thus not only become ineffective as a damper, but would contribute to an undesirable loss of preload. All things considered, the most advantageous place is in the thread interface area. Most effective damping results when the energy absorber is in good contact with both fastener elements.

Another variable — after such questions as what material and where to place it — is how much. Within practical limits, a larger volume of energy-absorbing nylon in the thread contact area yields better performance.

These considerations explain a number of things that have been observed as consistent test results. For example:

— The Elastic Stop® nut with a full red nylon collar of engineered proportions maintains tightness longer than any other locking device. The damping effectiveness of nylon has been proven the most reliable locking device yet developed in a nut/bolt assembly.

— nylon-damped fastener systems outperform any all-metal systems at maintaining tightness under similar shock and vibratory conditions.

— long all-metal nuts outperform short ones in maintaining tightness. Specifically, long-beam self-locking nuts tend to maintain damping tension better than shorter nuts that employ elliptically deformed collars to maintain locking torque. It must be remembered that the first stages of loosening occur without any rotation of the threaded members. Thus, locking torque is not a factor. Damping is.

. . . TO SUM UP THE THEORY

1

A theory of fastener loosening that would explain what is actually observed under service conditions has been needed for a long time. Accelerated vibration tests have been shown to have a dependable relationship to service conditions. An analysis of a large volume of vibration test results has provided the substantial basis for a valid causal theory of loosening.

2

Tightened fasteners on parts subjected to repeated shocks undergo a gradual reduction of bolt tension. This is probably a result of wear at important surfaces induced by vibration of the fasteners themselves. When bolt tension has dropped to a critical level in relation to vibration intensity, the nut begins to turn. Soon after that, it will spin off, if under continuing severe vibration.

3

For a given type of fastener system, the factors that promote loosening are vibration intensity and total number of impacts. The factors that tend to prevent loosening are: high pre-stress or bolt tension; the length of bolt under tensile stress; and vibration energy damping. Of these three, bolt tension and length are relatively inflexible, being determined by the individual fastening application. Damping, however, is of special importance and it is a variable subject to significant improvement.

WHAT THESE FACTS MEAN IN PRACTICE

It is now apparent that locking torque or prevailing torque is less important than had been assumed. Damping, on the other hand, is more important.

Preventing nut rotation is a useful (in many cases, a vital!) last-ditch safety measure, because it will keep a fastener in place after it has loosened — will prevent its falling off. But preventing nut rotation alone cannot assure fastener tightness.

A locknut with a full nylon locking ring will not rotate, whether it is tight or loose, except when wrenched. (Shock and vibration severe enough to cause rotation — comparable to vibration testing — would, in the typical case, be far beyond design capabilities of other parts, such as the bolts.) It will not only stay in place; the nut with the red nylon collar will also keep its initial tightness (and thereby maintain bolt pre-stress) longer under vibration and shock than any other threaded fastener.

Next best is the type of locknut that uses a pad of nylon (such as the ESlok® design with its tapered-edge red nylon patch on threads of the nut). An added advantage of the ESlok® device is that it requires no special machining — no grooves, holes or slots. Full strength of the metal is maintained, and this system can be applied to thin-wall members such as threaded rings or tube fittings.

Threaded fasteners must resist shock and vibration in high temperature environments beyond the range of plastic damping materials. All-metal nuts can be made to meet this need. They must be designed with considerable sophistication, and they must be manufactured with great precision to be effective. But we suspect that if a truly heat resistant insert material were available, we could build an insert type high temperature Elastic Stop® nut that would withstand vibration better than any all-metal type of locknut currently being produced.

This ESNA chart will help you avoid fastener failures

FASTENER TYPE	LOCKING DEVICE	RELATIVE PERFORMANCE
DAMPING, SELF-LOCKING	ESNA® Nylon ring	100
	ESlok® patch	25
ALL-METAL SELF-LOCKING, AIRCRAFT	Beam type	53
	Distorted thread	19
CASTELLATED NUT	Spring Pin	38
	Lockwire	18
	Cotter key	8
ALL-METAL SELF-LOCKING, COMMERCIAL	Beam type	4 to 17
	Distorted thread	1 to 10
PLAIN NUT	Spring-type lockwasher	5
	Tooth-type lockwasher	1
	None	1

Tightened fasteners loosen for a variety of reasons — shock, vibration, inadequate installation torque, wear between parts, bolt stretch and the ever present human error.

The Elastic Stop® nut with its integral red nylon locking collar, has proven in both laboratory and extensive field tests, to be the highest standard of locknut performance. The ESNA® red nylon collar can take extreme vibration and shock loads, remaining locked in place under the severest conditions.

With ESNA®'s relative vibration performance at 100 (see chart) the vibration resistance of alternative locking devices can be clearly evaluated.

This chart, the result of thousands of vibration tests under controlled laboratory conditions helps you select the nut locking device that will meet your requirements. When cost is a factor, consider the expense of stocking and handling of secondary locking elements (lockwashers, lockwires and cotter pins) and human error. Elastic Stop® nuts clearly become the most efficient choice.

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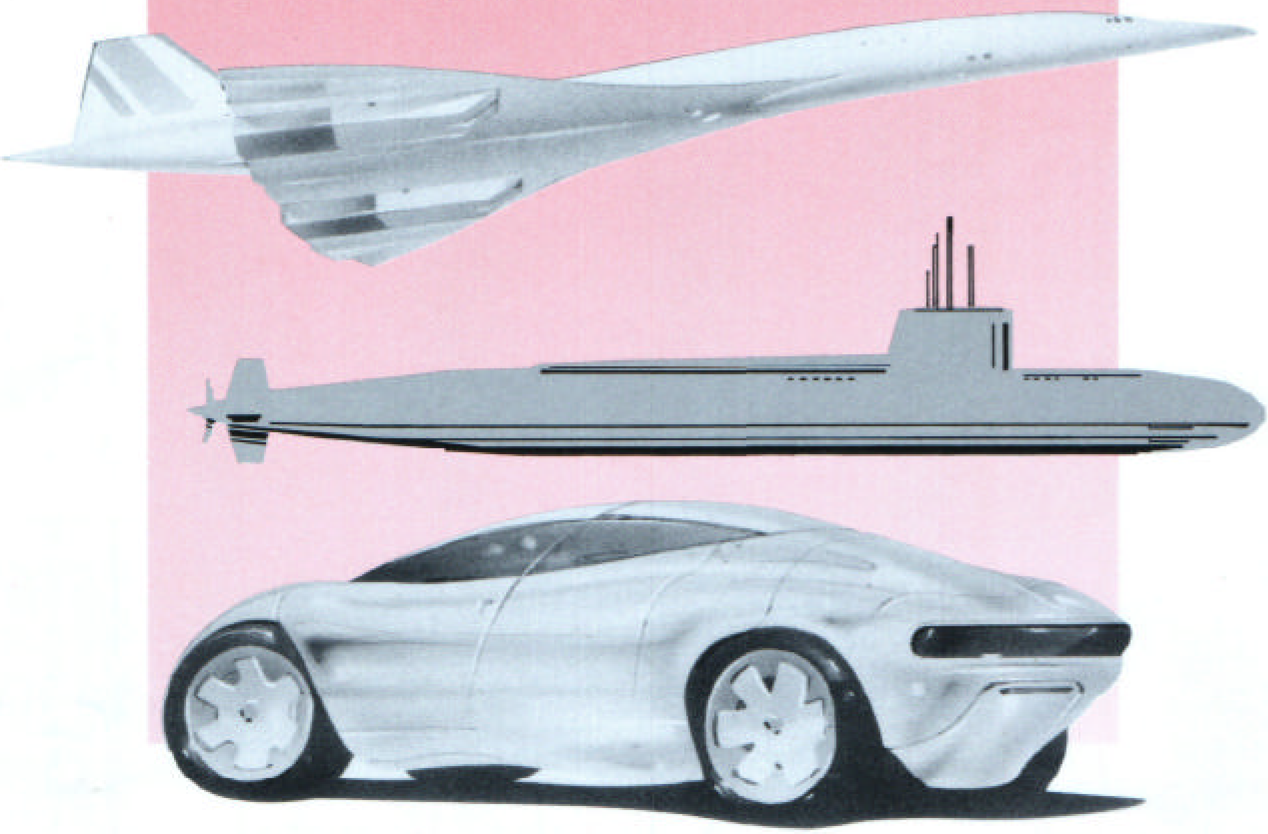

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